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A Joint Japan–China Research Project for Reducing Pollution in China in the Context of the Kyoto Protocol Clean Development Mechanism (CDM): Case Study of the Desulfurdized Bio-Coal Briquette Experiments in Shenyang and Chengdu

Hitoshi Hayami[a], Masao Nakamura[b,*] and Kanji Yoshioka[a]

[a] *Keio Economic Observatory, Keio University, Tokyo, Japan*
[b] *University of British Columbia, Vancouver, BC, Canada*

The Kyoto Protocol agreed on in 1997 allows some flexibility for developed countries in their implementations of their commitments to reduce emissions of CO_2 and other global warming gases. In particular developed countries may receive emission credits for facilitating international cooperation for developing clean development mechanisms (CDMs) between themselves and developing countries. CDMs must reduce emissions of global warming gases on a sustainable basis in the developing countries involved. Such CDMs are expected to be an important tool for Japan and other developed countries for achieving their Kyoto Protocol commitments to reduce their CO_2 emissions, but assessments and implementations of alternative CDMs require careful international joint research efforts. In this paper, we discuss our on-going Japan–China joint research to develop and evaluate bio-coal briquette (biobriquette), a new product to replace coal in some regions of China. Coal is a significant source of air pollution in China. The introduction of biobriquette use in China as a possible CDM for Japan is also discussed.

INTRODUCTION

China's rapid economic growth for the last two decades has had significant impacts on the atmospheric environment of China as well as other countries. In particular, China's massive consumption of coal has been causing serious air pollution domestically and also acid rain in the Pacific-Rim countries including Japan.[1] For these reasons it is important for policy makers, both in China and elsewhere, to explore various possibilities for application of a sustainable development strategy, by which economic growth and the health of the environment can coexist. Even if the notion of a sustainable development strategy is generally accepted, however, there is no universal principle to guide how such strategies can be formulated and implemented in developing countries.

Government policies on how to cope with environmental protection differ significantly from one country to another, and in China, like many

*Correspondence to: Faculty of Commerce, University of British Columbia, 2053 Main Mall, Vancouver, BC, Canada V6T 1Z2. E-mail: masao.nakamura@commerce.ubc.ca

other developing countries, economic development has clearly taken priority over protection of the domestic and global environment. In order not to be done in by China's massive desire to grow, any policy proposal to reduce environmental pollution in that country must be backed by well-grounded research showing that the implementation of the policy will lead to an improvement in the environment without a significant reduction in economic growth. This implies, for example, that any policy alternative involving replacing cheap coal which is abundantly available in China with more expensive imported oil as the primary source of energy will not be practical.

In this paper, we present a case study of a joint Japan–China experimental research project in which a practical method to reduce dependence of Chinese factories and households on pollution-generating coal was proposed and evaluated in terms of its feasibility for implementation and the potential problems of the transfer of required technologies. In this project Japan plays a role as a source of technology in the context of development aid. At the same time Japan was also interested in possibilities for gain from its environmental efforts in China in the form of environmental credits known as the clean development mechanism (CDM) in the Kyoto protocol. Such tradeoffs are possible because of the flexibility the Kyoto protocol agreed on in December 1997 allows for in implementation of the 1992 United Nations Framework Convention on Climate Change signed at the Rio de Janeiro Earth Summit. In particular, specific provisions are provided for: facilitating joint implementations of global warming gases reduction plans involving multiple Annex 1 (environmentally advanced, more recently called Annex B) countries; facilitating international cooperation for developing CDMs between Annex 1 countries and developing countries; and for setting up 'Global Environmental Facilities' which are financed by governmental aid through the international organizations (Toman and Cazorla, 1998; Grub *et al.*, 1999).

CDMs are expected to be an important tool for Japan and other Annex 1 countries for achieving their commitments in the Kyoto protocol to reduce their carbon dioxide (CO_2) emissions (by 6% below 1990 levels by years 2008–2012 in the case of Japan). Japan has been arguing that it would not be possible to achieve its Kyoto protocol commitments by relying entirely on its domestic energy conservation efforts given its already high level of energy efficiency. For this reason, Japan is expected to rely heavily on CDMs and other pollution trading mechanisms for fulfilling their international obligations in reducing its CO_2 emissions. Although no explicit rules have yet been devised to certify CDMs for the purpose of satisfying the emission reductions required by the Kyoto protocol, it is clear that the basic requirements for a CDM to be a satisfactory trading mechanism under the protocol will include credible scientific calculations of the sustainable amounts of emission reductions achieved by implementation of a CDM, together with a satisfactory level of technology transfer acceptable to the parties involved (Toman and Cazorla, 1998). The joint Japan–China research project reported in this paper is a possible candidate for a CDM that would be acceptable from these perspectives and that would satisfy the terms specified in the Kyoto protocol.

The organization of the rest of the paper is as follows. In the next section, we document the trend in China's energy consumption and show the factor decomposition of the energy elasticity for China including the elasticity of CO_2 consumption with respect to output. This information serves to motivate the types of new products considered in the rest of the paper. In a subsequent section, we discuss possible incentives that may induce China to become engaged in international joint research projects such as the one discussed here for reducing its CO_2 emissions. In another section, we discuss a proposed new product, bio-coal briquettes (also called biobriquette), as a possible replacement for the current raw coal presently used by the factories and households of China. The proposed product aims to achieve reductions in the emissions of both SO_x and CO_2 simultaneously and at reasonable cost. In addition we discuss using biobriquette ashes for improving the soil conditions in certain regions of China where serious soil erosion has been taking place. We also present the results of social experiments conducted in two Chinese cities where our joint research to promote the proposed product took place. Some simulation results on environmental improvements that might follow the adoption of the proposed new product in China are also presented. The paper ends with concluding remarks in the final section.

CO_2 AND SO_x EMISSIONS IN CHINA

China was already responsible for a sizable portion of global anthropogenic CO_2 emissions as early as 1990. China generated about 10% of the world's CO_2 emissions in 1990, which was twice as much as Japan's total CO_2 emissions. Although China's per capita CO_2 emissions are one-fifth the Japanese per capita CO_2 emissions, China's CO_2 emissions standardized by GDP (measured per US dollar of its GDP) are eight times what they are for Japan. This suggests that China's heavy dependence on fossil fuels with high carbon content and low energy efficiency was a threat to the global environment even when its economy was still relatively small by global standards.

The situation seems considerably worse for SO_x emissions. According to our estimates China emitted a total of 23.4 million tonnes (SO_2 equivalents) of SO_x gases in 1987. The figure for China is 6.7 times what the corresponding figure is for Japan.[2] China's SO_x emission exceeds that of Japan by 11.5 t per one US$ million of GDP. Unlike CO_2 which causes no immediate health and environmental hazards, SO_x causes human health problems (e.g. respiratory ailments) in localities and also causes acid rain domestically as well as in the neighbouring countries.[3] Reductions in SO_x emissions are, therefore, a much more urgent issue for China. In recent years, the Chinese government began penalizing factories that use coal with high sulfur content.

Certain characteristics of the Chinese economy tend to help keep China's emissions of these gases lower than they otherwise would be. For example, compared to consumers in Japan, consumers in China, at least for now, purchase much less in the way of products whose production requires output from heavy industries (Hayami *et al.*, 1997). This is helpful from the environmental point of view since heavy industries in China generally emit large amounts of pollutants including SO_x and CO_2.

SO_x Emissions

There are several major factors that contribute to China's high levels of SO_x emissions. The most significant of these is the pattern of China's fuel consumption that depends heavily on coal with relatively high sulphur content.[4] China depends on coal for more than three quarters (76.8% in 1990) of its primary energy supply. (About 1 billion tonnes of coal is consumed annually.) Other countries depend much less on coal: 24.1% for the US, 30.9% for Germany, 42.2% for the former Soviet Union, 17.2% for Japan, 35% for other Asian countries (excluding China and Japan), and 21.6% for the world. The coal problem for China is made worse by the low levels of energy efficiency that characterizes the industrial and household sector users of the coal, resulting in an average Chinese demand for energy to produce a unit of final output which is much larger than the corresponding figure for any one of the developed countries and even for some other developing countries.[5] Another factor is the very low diffusion of coal sulphur-removal equipment and associated technologies. Even if this sort of equipment is made available in China by international development aid programs, the costs of operating the equipment (estimated to be about 1% of the electricity generated in the case of coal power generators) may result in the equipment not being used.

There are other obstacles that impede China's efforts to reduce its dependence on coal. The first is China's domestic employment structure. In particular, the coal industry still provides significant amounts of employment in many regions. Another difficulty is that China as a nation does not have alternative large domestic supplies of other energy sources to replace coal, even though some regions of China do have abundant natural gas.

Oil Imports and Coal

Over time China's oil imports have significantly increased. The imports of crude oil grew by 45.6% annually between 1990 and 1995.[6] Such a high rate of growth in oil imports was not sustainable in the long run, given China's limited foreign reserves and the capacity of the world oil market. As a result, the annual growth rate of China's crude oil imports decreased to about 6% per annum from 1996 on.

Elasticity of Energy Consumption with Respect to GDP

Nonetheless, Chinese officials have often argued to us that China's rapid economic growth did not contribute to the emission of CO_2 as much as one would expect from the experience of developed countries. Their argument is based on China's energy elasticity with respect to GDP growth, which is estimated to be about 0.6 at the aggregate level. This figure is relatively low by comparison with estimates for developed countries. For China, this estimate implies that its energy consumption has grown at a rate of only 0.6% for every percentage point growth of its GDP. On the other hand, estimated energy elasticities for developed countries such as Japan and the US are much higher and exceed one.

We discuss below why China's energy elasticity with respect to GDP has been relatively low and nearly constant over a period of rapid economic growth for that nation. We have estimated energy elasticities with respect to Gross Domestic Product by industry (Table 1). Table 1 shows that, although energy elasticity estimates for the entire industry is less than 1, industry-specific estimates vary significantly: for example, estimates range from highs of 1.6 for the electric power industry and 1.7 for the non-metallic mineral industry to the lows of 0.3 for the textile and rail and transport industries, 0.4 for the paper industry, and 0.1 for the construction industry.[7] As Table 1 shows, it is the latter industries (e.g. paper, construction, transport) with relatively low energy elasticities that grew very rapidly during this period compared to more energy-intensive industries such as electric power. This explains the relative constancy of China's energy elasticity during a rapid economic growth period.

Table 2 (first panel) shows the contributions of various factors to the change in China's energy elasticity over the period 1985–1996. This energy elasticity for the entire economy increased by about 0.9% points during the period. The factor

Table 1. Real GDP Growth and Energy Elasticity by Industry: China, 1985–1996

Industry	GDP growth rate	Energy elasticity with respect to GDP
Electric power	0.058939	1.5863
Iron and steel	—	0.8500
Ferrous & non-ferrous metals	0.078682	1.3766
Non-metallic minerals	0.072691	1.7229
Chemicals	0.041991	0.6264
Food, beverage, tobacco	0.098211	0.7328
Textile, clothing, footwear	0.090187	0.2795
Paper and printing products	0.134811	0.4679
Construction	0.136579	0.1196
Railway and road transport	0.078325	0.2701
Sea and air transport	0.107754	1.1379
Other transport	0.076637	0.6822
Total	0.08008	0.7383

Source: Calculated using data from: China State Statistical Bureau (ed.), The Composition of Final Energy Consumption: China, 1984–1996, China Statistical Yearbook, Yearbook of Energy Statistics, Cambridge Econometrics and Hayami (2000).

Table 2. The Decomposition of the Change in Energy and CO_2 Elasticity with Respect to GDP: China, 1985–1996

Total change in elasticity	Weights for industrial sectors	Growth rates for industrial sectors	Change in intra-sector elasticity	Change in cross-sector elasticity
Decomposition of the change in energy elasticity over the period 1985–1996				
0.0865	0.0169	−0.0871	0.0981	−0.0112
Decomposition of the change in CO_2 elasticity over the period 1985–1996				
0.0775	0.0191	−0.0964	0.0951	−0.0118

Source: Calculated using data from: China State Statistical Bureau (ed.), The Composition of Final Energy Consumption: China, 1984–1996, China Statistical Yearbook, Yearbook of Energy Statistics; Cambridge Econometrics and Hayami (2000).

which made the largest contribution to the change (an increase) in the energy elasticity is the increase in the elasticity within each industrial sector (see the intra-sector elasticity estimates in Table 2). The growth factor makes a large negative contribution to the change in the elasticity. This reflects the fact that relatively fast growing industries have decreased their energy elasticities during this time period. The weights of the respective sectors make a small but positive contribution to the change in the elasticity, suggesting the positive contributions of the GDP shares of the respective industries. The small magnitude of weight means also that the industries with relatively large energy elasticities have increased their GDP share in the economy, but their volumes are still small.

CO_2 Emission

We have also calculated the factors that had contributed to the change in the elasticity of CO_2 emissions with respect to GDP (Table 2, second panel). The patterns for the decompositions of energy and CO_2 elasticities presented in Table 2 are quite similar. This is expected, since CO_2 emissions occur when fossil fuels such as coal are consumed.

China's energy elasticity is still relatively small compared to the energy elasticities observed for developed countries, but has nevertheless been increasing in recent years. Unfortunately, as discussed above, as growth rates for industries with low energy elasticities (e.g. labour-intensive industries) decline, capital-intensive industries are expected to become more dominant and the total energy elasticity (and CO_2 elasticity) for the Chinese economy can be expected to increase rapidly. The Chinese government does promote the use of natural gas in areas of the country such as Sichuan where there are large reserves of natural gas. But many other areas in China have access to an abundant supply of coal but little or no natural gas, and heavy industries in China historically developed near where there were abundant coal supplies. These areas will continue to depend on coal for the foreseeable future. For these reasons, China as a country is expected to continue to depend on coal as its primary source of energy for a long time to come. It seems clear that any new policy initiative to reduce China's emissions of both SO_x and CO_2 will need to take into account the role coal does and is expected to continue to play in China's energy supply. In the next section, we discuss the international political realities of the environmental movement facing Japan in its efforts to achieve its Kyoto protocol targets for CO_2 reductions.

INTERNATIONAL COOPERATION IN THE KYOTO PROTOCOL FRAMEWORK: INCENTIVES FOR A JOINT R&D PROJECT

As we have argued above, reductions of the emissions of such pollutants as CO_2 and SO_x are an important and urgent issue for China. It is also a serious issue for Japan from international political perspectives since Japan did make a commitment to bring down its CO_2 emission level over the period of 2008–2012 to a level which is 6% below Japan's 1990 level. There is general agreement among the experts that Japan will not be able to achieve such a large reduction in its CO_2 emissions solely by relying on increasing the efficiency of its domestic energy use, since Japan had already achieved a relatively high level of energy efficiency by the mid-1980s following its massive energy conservation efforts during and after the two oil crises in the 1970s.

One feasible way for Japan to achieve its CO_2 emission goal agreed to in Kyoto is to take advantage of alternative CDMs for carbon credits outside Japan, since this would substitute for real reductions in energy use in Japan's domestic economy. Possible CDMs under consideration include foreign direct investment (FDI) in alternative energy-saving technologies and in plantations of trees in non-forested land areas. For example, some Japanese manufacturing firms have already started investing in growing trees in Australia with express expectations that they will be able to secure credits for CO_2 emission in the future.[8]

These considerations have led us to conclude that it might be possible to align the incentives of both Japan and China along lines of their respective environmental policies. A joint research project whose experience is reported in this paper was undertaken to investigate the feasibility of such a joint environmental strategy in which Japan would invest in China for improving China's coal combustion efficiency and also for planting and growing trees. Since implementing our research findings in practice would require cooperation of the localities involved in China, we have chosen to collaborate with Chinese counterparts at the local (city) level rather than provincial or national levels. This decision was also based on our understanding of some concerns raised in some Chinese localities which were often asked in the past to cooperate by Chinese or Japanese central governments to complete many ODA projects from Japan. The fundamental problem seems to have been that most of the budgets for those ODA projects were split between China's central and provincial governments with little left for the local governments involved. This happened because the Japanese government dealt only with the Chinese (central) government in determining their ODA projects in China, while most of the implementations takes place at the local level. Because of the lack of funds (and hence benefits) to them, few localities have been willing to cooperate in such projects. This suggests the importance of involving relevant localities as partners in these projects from the beginning.

Process of Cooperation

Our cooperative efforts have been concentrated mostly at the grass-roots level. To convince citizens in Chinese localities of the potential benefits of the joint research project, we conducted detailed surveys of the environment and also the health statuses of inhabitants in the localities. These surveys would not have been possible without the collaboration of the local researchers and city governments.[9] Ascertaining the existence and the extent of health problems from which the local Chinese inhabitants suffer was particularly important for securing the kinds of local cooperation we needed for the project.[10] To promote our proposed product (bio-coal briquette) as a possible substitute for coal, detailed cost and benefit calculations were conducted to assess the improvement in the environment that could be achieved through the use of this product. Local production of the product was also promoted through cooperation from our local collaborators. One operation involving massive amounts of labour that took place (and is still taking place) is planting trees on the soil that was improved with the ashes obtained from burned biobriquette. This labour was supplied almost entirely by local volunteers including students and Chinese Red Army personnel. This process is on-going and the impacts of the new product on the environment continues to be monitored.

In the next section, we describe some essential, operational aspects of the joint Japan–China R&D project: first, the development and assessment of the biobriquette, a new coal and biomass-based product, promotion of which may significantly reduce both SO_x and CO_2 emissions; and, secondly, how such a product can be expected to also combat desertification, a serious problem in some regions in China.

A DESULFURDIZED BIO-COAL BRIQUETTE (BIOBRIQUETTE) EXPERIMENT IN SHENYANG AND CHENGDU FOR REDUCING SO_x AND CO_2 EMISSIONS, WITH AN APPLICATION TO AFFORESTATION

We have argued in the previous section that one practical approach to reducing SO_x and CO_2 emissions in China would permit taking advantage of coal which is abundantly available in China. A traditional way to reduce the emissions of SO_x and other pollutants generated by coal-burning equipment such as power generators and boilers is to install sulphur removing equipment. This sort of anti-pollution equipment is widely used in developed countries to avoid the types of air pollution problems caused by coal and which are discussed above. It seems fair to say, however, that the adoption of equipment of this sort in China has not been successful. For example, significant numbers and varieties of sulphur removing technologies and equipment were imported into China over the last decade by various Japanese manufacturers using the Japanese ODA budget, but relatively little of this equipment is being used now on a regular daily basis.

There are a number of reasons why this anti-pollution equipment has not become more widely operational in China. First, the types of equipment sold under the ODA and other international aid programs are often too sophisticated and expensive for practical implementation in China. ODA programs often impose little constraint on the equipment purchase price and hence the Chinese government typically wants to buy equipment with the best available technology. The equipment manufacturers would also like to sell the newest (and often most) expensive equipment since that is typically the most profitable equipment for them to sell.

This new anti-pollution equipment is generally not only expensive to purchase on a commercial basis but also expensive to operate. For example, at a coal power generation a few per cent of the power generated may have to be allocated to run the installed sulphur removing equipment. In general, few managers of Chinese factories which use coal seem to be willing to divert even 1% of the electricity used at the factories to operate anti-pollution equipment. Another practical problem arising from running this sort of equipment is how to dispose of the sulphur resulting from the sulphur-removal process.

In the rest of this section, we describe the development of a new product called bio-coal briquette (biobriquette) which addresses the issues raised above for implementing anti-pollution measures in China.

Biobriquette

Our first priority is to produce a product which uses coal as a raw material, generates little SO_x and less CO_2, and is usable as a replacement for coal in many coal burning applications. Noting that sulphur contained in coal can be removed by limestone or its equivalents, coal combustion engineers and other coal specialists in our team recommend that we produce biobriquette which is made from powdered coal, limestone, grain skin and other types of biomass. These raw materials are compressed under a very high compression pressure into biobriquette. Because of its lime content, biobriquette generates much less in the way of SO_x emissions than coal while providing a significantly better combustion efficiency than the original coal itself. Production of biobriquettes requires advanced technologies for both making powdered coal and generating the required very high compression. Neither of these technologies are currently available in China. One Japanese company (Hosokawa Micron Corporation) subsequently joined in the research team, however, and transferred some of their technologies including the methods of operating their compression machinery to the Chinese operation sites of the project.

Locations of the Project Operation

We selected two cities, Chengdu and Shenyang, for conducting our research experiments, which consisted of production of biobriquette, using this product locally, measuring the efficiency of the combustion and the emission levels, and identifying relevant research questions. These two cities were chosen for a variety of reasons. One is that some team members were already familiar with many aspects of these cities. Another reason is that these cities have certain contrasting geographic and other characteristics which may turn out to be useful in terms of adding variation to our experimental design. For example, Chengdu is located in the interior part of China where it is relatively warm and wet, while Shenyang is located in the northeastern part of China where it is cold and dry. Chengdu has a natural gas reserve, while Shenyang does not. Also unlike other cities on the southeast coast of China, both Chengdu and Shenyang have been left behind in China's recent modernization trend.

Desertification Problem in Shenyang

Shenyang grows corn and the other vegetables in large quantities. One serious problem facing agriculture in Shenyang is the rapidly progressing desertification of land in the northwestern part of Shenyang. The Kareqin Desert extends from Northwest Shenyang all the way to Inner Mongolia. The desertification is threatening the viability of the corn plantation in Shenyang. It was part of our plan to take advantage of biobriquette ashes as a means for combating the desertification. To prevent further desertification of land in the Shenyang area, massive soil improvement and afforestation are required. The soil there contains a large amount of alkali salt, and it is known that gypsum can be used to neutralize alkali salt. We also knew that biobriquette ashes, like gypsum, would have similar soil neutralizing effects, which would be useful for maintaining corn crops and planting trees in Shenyang. However, the degree of the biobriquette's neutralizing properties were unknown and would need to be ascertained from our on-site experiments.

Manufacturing of Biobriquette

Table 3 shows examples of some biobriquette making machines, which were installed in Chengdu and Shenyang. (See also Figure 1.) The machines are experimental and hence their production capacity is not yet very high. Nevertheless, the biobriquette produced locally have shown

Table 3. Installed Biobriquette Production Equipment

Chengdu	
Production capacity	200–250 kg/h
Electricity consumption	303.7 kW
Annual production at full employment (= 225 kg/h × 15 h/day × 250 days/year)	843.8 t/year
Shenyang	
Production capacity	50 kg/h
Electricity consumption	10 kW
Annual production at full employment (= 50 kg/h × 15 h/day × 250 days/year	187.5 t/year

Source: Yang (2000) and Nitta (2000).

result in the expected rates of reduction in emissions of SO_x compared to raw coal (Table 4).

In Chengdu Chinese researchers have conducted experiments to measure the emission characteristics of the three types of fuels: hard coal, prototype biobriquette (Type A) and improved-type biobriquette (Type B). Table 4 also shows that about 70% reduction of SO_x emissions over the reference (hard coal combustion) has been achieved using Type B briobriquette. (See Figure 2.)

Cost of Production

We have also estimated optimal plant size and the optimal number of biobriquette producing

Figure 1. The sign for the joint Japan–China biobriquette experimental factory (above) and the biobriquette manufacturing machine (below).

Table 4. Pollutants Emissions and Thermal Efficiency: A Comparison Between Coal and Biobriquette

Shenyang

	Coal	Biobriquette
Dust (mg/Nm)	112–121	42–46 (63%)[a]
SO_2 (mg/Nm)	742–976	307–314 (64%)
Gross calorific value (kJ/kg)	15355–23012	16 700
Thermal efficiency[b]	100	111

Chengdu (average over plants)

		Biobriquette[c]	
	Coal	Type A	Type B
Dust (mg/Nm)	—	—	—
SO_2 (mg/Nm)	2007	654 (67.4%)	601 (70.1%)
Gross calorific value (kJ/kg)	20 188	16 207	16 207
Thermal efficiency[b]	100	104	107

[a] Numbers in parentheses represent improvements (%) for biobriquette over coal.
[b] Thermal efficiency is measured as the amount of time required to boil the same amount of water using a stove and a pan.
[c] Type A biobriquette are made from coal, biomass, straw and CaO. Type B biobriquette are made from Type A biobriquette mixed with such activators as iron oxide, potassium manganate (an oxidising agent) and NaCl.
Source: Kim *et al.* (2001) and Hashimoto *et al.* (2001, Tables 5 and 4).

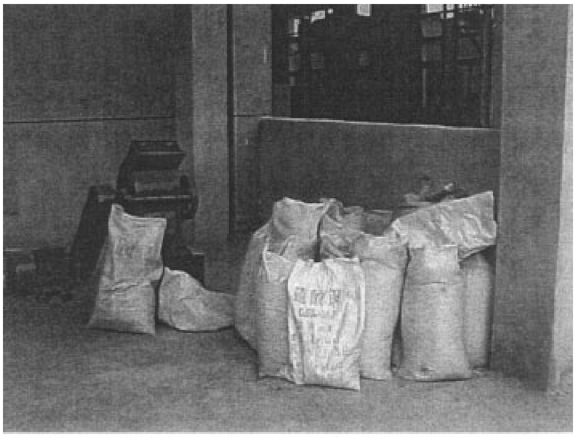

Figure 2. Raw materials (above) and produced biobriquette (below).

machines for a given market size (Table 5).[11] Based on the results, we have estimated biobriquette production costs for both Chengdu and Shenyang. Estimates for variable and fixed costs are presented, respectively, in Tables 6 and 7. In Chengdu, substantial reductions in variable cost (from 250 to 146 Yuan per tonne of briquette produced) were achieved when we moved from experimental to production plants. A larger scale of production allows plants to be able to take advantage of lower transportation and labour costs. In Shenyang, variable cost (205 Yuan) was estimated to be higher than in Chengdu (146 Yuan). The primary reason for the difference in variable cost between the two cities is the higher cost of coal in Shenyang compared with Chengdu (Table 6). Coal in Shenyang is of higher quality, containing more calorimetric energy than coal in Chengdu. Shenyang coal also produces 45% less SO_x emissions than Chengdu coal. Estimates for fixed production cost are presented in Table 7. Assuming the operating life of production equipment to be 10 years, we estimate that the production of 1 t of briquette costs 277 Yuan at the experimental run in Chengdu, 4 Yuan at the production run in Chengdu and 19 Yuan at the production run in Shenyang. Using figures in Tables 6 and 7 we have estimated the total cost of production (Table 8). The last row of Table 8 shows our cost estimates for biobriquette especially developed for stove use. Production of biobriquette for stoves requires somewhat less raw material than for industrial boiler use, resulting in lower production costs.

Technology

Our local Chinese collaborators view large production plants to be essential for biobriquette to become competitive with raw coal, given the various high cost operations involved in preparing biobriquette (e.g. processing coal and biomass by electric power and then pressing these materials into biobriquette). Our cost estimates suggest, however, that there is an optimal size for a manufacturing plant and there is an optimal number of plants for a given market size. The fact that relatively small plants can be optimal is an

Table 5. Optimal Plant Capacity and Market Size

Market size (*M*) (10 000 t/year)	Daily output (*q* t/h) (annual output (tonnes/year))	Number of machines installed (*n*)
10	1.19 (8330)	12
25	1.53 (10 710)	23
50	1.80 (12 600)	40
100	2.04 (14 280)	70
150	2.18 (15 260)	98
200	2.27 (15 890)	126

Source: Yoshioka *et al.* (2001).

Table 6. Variable Cost Estimates for Biobriquette Production

Item (Yuan)	Inputs per tonne of briquette	Unit material price	Unit production cost
Chengdu (*production plant*)			
Raw material			109.26
Powdered coal	664.0 kg	0.095 Yuan/kg	63.08
Powdered limestone	170.0 kg	0.150 Yuan/kg	25.50
Sawdust	124.5 kg	0.150 Yuan/kg	18.68
Straw	41.5 kg	0.050 Yuan/kg	2.08
Electricity	30.0 kWh	0.570 Yuan/kWh	17.10
Transportation			10.00
Labour			10.00
Total variable cost			146.44
Chengdu (*experimental production plant*)			
Raw material			109.26
Electricity	131.0 kWh	0.570 Yuan/kWh	74.67
Transportation			35.73
Labour			30.00
Total variable cost			249.66
Shenyang (*production plant*)			
Raw material			142.43
Coal	423.7 kg	0.170 Yuan/kg	72.02
Coal	464.3 kg	0.120 Yuan/kg	55.72
Limestone	51.5 kg	0.050 Yuan/kg	2.58
Straw	132.0 kg	0.080 Yuan/kg	10.56
Drying material		10 Yuan/t	8.60
Electricity	32.0 kWh	0.600 Yuan/kWh	19.20
Transportation		15 Yuan/t	16.20
Labour		1040 Yuan/month	8.33
Administration			10.40
Total variable cost			205.14

Source: Hayami *et al*. (2001).

important consideration for practical implementation of our biobriquette products, since this would allow smaller plants to be located in various localities. The kinds of coal and biomass available vary significantly from one locality to another and hence a smaller optimal plant size would allow us to implement the manufacturing plants which are most suitable for the specific local conditions.

The End of Experiments in Chengdu

Recently the Chinese government decided to promote natural gas in Sichuan Province, and the city of Chengdu then lost interest in biobriquette completely. As a result, our joint research project in Chengdu was discontinued and all research and production equipment from that location was moved to Shenyang. Our project has been continuing in Shenyang, where no natural gas reserves exist.

Results from the Shenyang Experiment

Shenyang consumed 9.53 million tonnes of coal in 2000, of which the household sector, the electric power generation sector and the remaining industrial sector, respectively, consumed 3.97, 2.54 and 3.00 million tonnes. In practice biobriquette cannot be a full substitute for coal. For example, biobriquette cannot be used for electric power generation. We estimate that biobriquette can be used to substitute for atmost 50% of coal use.

Table 7. Manufacturing Cost of Biobriquette Producing Equipment (Yuan)

Chengdu (experimental plant)	
Main equipment	12 000 000
Peripheral equipment	
Conveyor belt	30 000
Magnetic separator	8000
Grinder for biomass	10 000
Grinder for limestone	9000
Grinder for coal	8000
Dryer	200 000
Mixer	34 000
Sieve: vibrating screens	30 000
Dust collector	12 000
Total	2 341 000
Unit fixed cost per annum per tonne of output	277.44
Chengdu (annual production: 10 000 t)	
Main equipment	1 170 000
Peripheral equipment	
Conveyor belt	11 000
Magnetic separator	12 000
Grinder for biomass	17 000
Grinder for coal	12 000
Dryer	13 000
Mixer	17 000
Sieve (vibrating screens)	11 000
Total	263 000
Total including installation cost	400 000
Unit fixed cost per annum per tonne of output	4.00
Shenyang (annual production: 30 000 t)	
Main equipment	3 000 000
Depreciation for the main equipment per year	300 000
Depreciation for the peripheral equipment per year	259 000
Unit fixed cost per annum per tonne of output	18.63

Notes: The main equipment produces biobriquette with high pressure. Estimated costs are based on Chinese prices in 1999 and 2000. The main equipment for experimental production is expensive because it was made in Japan. Its annual production capacity is assumed to be 843.8 t. Other equipment are assumed to be made in China. Depreciation is assumed to be the cost at purchase divided by the estimated number of years of service.
Source: Yang (2000) and Liu (2000).

Using biobriquette producing machines in Shenyang, we were able to obtain data on feasible substitution possibilities between coal and biobriquette. One important factor which affects such substitution ratios is the efficiency of thermal conversion for the two fuels. Conversion efficiency depends on the temperature at which a fuel is burnt, and burning fuel at a higher temperature results in a higher conversion efficiency. For example, biobriquette generally burns at a higher temperature than coal and hence possesses a higher conversion efficiency than coal. Furthermore, the higher the efficiency is for biobriquette, the less briquette we need to replace coal. In our experiments we have found that there are three levels of conversion efficiency (1.00, 1.04 and 1.11 in Table 9) to consider. (Table 10 shows calorific values for the various types of coal available in Shenyang.) For example, if the conversion efficiency is 1.00,then the entire consumption of coal used for non-power generation purposes in Shenyang in 2000 (6.97 million tonnes) could be replaced by 7.42 million tonnes of biobriquette (Table 9). We also see from Table 8, for example, that if the conversion efficiency is 1.04, then 1.43 million tonnes of biobriquette will replace 20% of Shenyang's non-power generation coal.

Table 11 presents results from our simulation experiments in which the cost of achieving a 1 t of reduction in CO_2 emissions and other related figures were calculated for various values for the market size and conversion efficiency. For example, the last row of Table 11 shows that the market size for biobriquette when the conversion efficiency is 1 is 3.709 million tonnes, which substitutes for 50% of Shenyang's non-power generation coal (Table 9). To produce this amount of biobriquette, we need 507 biobriquette producing machines, the production cost of which is 87.9 million Yuan. The price of the biobriquette

Table 8. Total Unit Cost of Biobriquette Production (Yuan per tonne)

Chengdu: experimental production run/biobriquette	527.10
Chengdu: annual 10 000-tonne production run/biobriquette	150.44
Shenyang: annual 30 000-tonne production run/biobriquette for boilers	223.77
Shenyang: annual 30 000-tonne production run/biobriquette for stoves	200.00

Notes: The productive life of the equipment for Chengdu with an annual output of 10 000 t is assumed to be 10 years. Liu (2000) estimates the unit cost of production for biobriquette for stove use. The cost of raw material for biobriquette for stoves is lower than that for briquette for boilers.
Source: Yang (2000) and Liu (2000).

Table 9. Substitution Between Coal and Biobriquette: Shenyang (2000)

	Coal consumption (tonnes)	Coal consumption ($TJ = 10^{12}$ J)	Biobriquette: equivalent consumption million (tonnes)		
Thermal conversion efficiency	1.00	1.00	1.00	1.04	1.11
100% (total substitution)	6 970 000	123 882	7.418	7.133	6.683
1%	69 700	1 239	0.074	0.071	0.067
5%	348 500	6 194	0.371	0.357	0.334
10%	697 000	12 388	0.742	0.713	0.668
20%	1 394 000	24 776	1.484	1.427	1.337
50%	3 485 000	61 941	3 709	3.566	3.341

Notes: Total coal consumption does not include coal used for power generation. Calorific value for biobriquette is assumed to be 16 700 kJ/kg.
Source: Hayami *et al.* (2001); coal consumption in Shenyang was obtained from the Shenyang Environmental Protection Bureau.

Table 10. Carbon Contents and Calorific Values for Bio-Coal Mixtures, and the Price of Coal: Shenyang in 1999

	(J/g)	Price per tonne (Yuan/t)	Carbon contents in weight
Fushun coal	23 012	170	0.7618
Hongyang coal	21 757	140	0.7237
213 Lignite	15 355	100	0.4855
Lignite	12 970	110	0.3922
Shenbei			
Tiefa coal	15 481	120	0.4905
Xima coal	22 175	130	0.7368
Biomass	15 086	80	0.4950
Limestone	0	50	0.1220

Notes: The carbon contents of coal are estimated by the authors using available data for calorific values and carbon contents. The carbon contents for biomass are from Kim *et al.* (2001). The carbon content for limestone is from Asakura *et al.* (2001). Carbons emitted by biomass are not included in our estimation of the carbon content for biobriquette.
Source: Liu (2000) and Hayami *et al.* (2001).

produced this way is 210.62 Yuan per tonne. Consumption of these biobriquette will emit 6.598 million tonnes of CO_2, which is 0.698 million tonnes less than the amount of CO_2 emitted from the equivalent coal consumption. The cost to achieve a reduction in 1 t of CO_2 emissions is estimated to be 484 Yuan.

Desertification in Shengyan

The Kareqin Desert is located about 300 km away from Shenyang, and the current climate conditions are causing desertification of soil in Shenyang as a result. This implies, among other things, that the very hard alkali soil of the desert is spreading into Shenyang, threatening corn crops, the primary agricultural product of this region. The hard alkali desert soil can be improved by adding ashes obtained from burned biobriquette which contain acid in the form of sulphur. Our on-going experiment in Shenyang, however, seems to suggest that the sulphur content of biobriquette ashes alone is not enough to adequately improve the desert soil. Clearly more experiments are needed to find the right acid mix to combat desertification.[12] Quite ironically, preventing desertification requires a lot of sulphur in order to produce gypsum equivalents. In Shenyang, the soil needs more sulphur, but the atmosphere contains too much sulphur.

Afforestation of the Local Government

Another on-going activity of our joint research project involves planting trees in Shenyang. In

Table 11. The Price, Capacity and CO_2 Emission for Biobriquette: 16 700 kJ/kg A Simulation Study in Shenyang

Thermal (conversion) efficiency (coal = 1)	Market size (tonnes)	Number of main equipment	Production cost of the main equipment (Yuan)	CO_2 emissions from biobriquette (tonnes)	Reduction in CO_2 emissions (tonnes)	Price of biobriquette (Yuan/ton)	Cost to achieve reduction in CO_2 emissions (Yuan)
1.11	66 827	15	10 259 191	118 875	27 055	223.60	225.12
1.04	71 325	16	10 580 002	126 876	19 054	223.08	370.49
1.00	74 178	16	10 777 212	131 951	13 979	222.78	548.90
1.11	334 136	56	22 964 569	594 374	135 277	215.12	204.17
1.04	356 639	59	23 771 195	634 404	95 247	214.91	340.03
1.00	370 905	61	24 271 758	659 780	69 871	214.79	506.76
1.11	668 297	103	33 361 327	1 188 793	270 509	213.24	199.58
1.04	713 279	109	34 575 576	1 268 808	190 495	213.09	333.22
1.00	741 810	113	35 329 675	1 319 560	139 742	213.01	497.30
1.11	1 336 594	194	49 044 913	2 377 585	541 019	211.92	196.31
1.04	1 426 557	206	50 879 384	2 537 615	380 989	211.81	328.43
1.00	1 483 619	213	52 018 844	2 639 120	279 484	211.75	490.63
1.11	3 341 485	459	82 737 777	5 943 963	1 352 547	210.72	193.36
1.04	3 566 393	489	85 910 637	6 344 038	952 473	210.66	324.09
1.00	3 709 048	507	87 881 578	6 597 799	698 711	210.62	484.60

Notes: Thermal efficiency levels are from Table 4. Market size was derived from the total calorific value of coal and biobriquette consumed. The number of the main equipment and production cost of the main equipment were estimated using the cost function (as an index of the production cost) given in Yoshioka *et al*. (2001). CO_2 emissions from biobriquette were calculated from the estimated carbon contents and market size for biobriquette. The CO_2 reduction denotes the difference between the emissions from biobriquette and coal (Table 8). The CO_2 content of coal is estimated to be 0.571. The price of biobriquette is the price per tonne based on the sum of the variable costs given in Table 6 and the production cost of the main equipment (column 4 above of this Table). More specifically, the variable costs include the costs for raw materials (as much as 16 700 kJ/kg in terms of the calorimetric energy content), the cost for labour and the fixed cost other than the cost of the main equipment. CO_2 reduction cost (Yuan per tonne) is calculated as the cost of additional investment required to achieve the reduction in CO_2 emissions by 1 t assuming the average price of coal to be 127 Yuan per tonne.

addition to their contribution to soil improvement, strategically planted trees will block the strong west wind that brings in sand from the desert to Shenyang. It was concluded that afforestation is the best measure to block the west wind from the desert. Afforestation also provides a sink for absorbing CO_2. For these reasons, even though it was not a part of the original research plan of our project, afforestation was added to the agenda of our project at this point. The city government of Shenyang, which is the capital of Liaoning Province, was quite willing to take part in our afforestation activity. They were able to mobilize many 'volunteers,' including school children and Chinese Red Army personnel (Figure 3).[13] We found this cooperation from these governments essential for our project.

Figure 3. Tree planting festival in Shenyang (March 1999).

CONCLUDING REMARKS

In China, as in many other countries, success in promotion of an environmental project like ours requires an incentive system which is compatible with the economic benefits and also politically sustainability of the local community. For a CDM proposal such as ours to qualify under the terms of the Kyoto Protocol framework, actual implementation of the mechanisms proposed must pay attention to the incentives of both the local and the Japanese participants, and these mechanisms must be sustainable in the long run. We have reported in this paper on various aspects of our

Figure 4. Tree plantation and two monuments (September 2000).

on-going Japan–China joint research project which provides support for adoption as a CDM of our newly developed product, biobriquette, and related activities such as afforestation in Shenyang.

As in many joint venture project involving foreign entities, serious economic and political risks of a non-contractible nature exist for this project. For example, the sudden decision by the Chinese government to promote natural gas in Chengdu, which led to the subsequent termination of our joint project in that city, can be understood within such a risk framework.[14] Potential unintended spillovers of the Japanese technology transferred to China and also potential reductions in efforts by Chinese local volunteers that are devoted to the joint project are other examples of noncontractible events which might impede the Japanese side from securing the originally planned emission credits.

Nevertheless, at this time local farmers in Shenyang continue to maintain the forest of the trees planted by our project, which now extends over an area 15 km long and 100 m wide. We plan to expand the size of the forest to an area as large as 24 km long and 100 m wide within the next 2 years. Figure 4 shows our treed plantation and two monuments beside it that were build by the local government for this joint research project. One of them says: the forest of the China–Japan friendship, 100 mile of the Green Great Wall, will last for centuries.

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NOTES

1. Recently released photo images of Northeast Asia taken by NASA's space satellite show massive quantities of air-borne pollutants and car exhaust gas emitted by Chinese factories and cars, respectively, extending from China to the Korean Peninsula and Japan (Asahi Shimbun, January 17, 2002).
2. See Hayami and Kiji (1997).
3. Significant numbers of children in some regions of China suffer from pollution-caused illnesses including wheezing with a lot of phlegm (Yoshioka, 1999).
4. Detailed health surveys were conducted in 1991 and 1992 in Shenyang and Chengdu by members of the joint Japan–China research team to find the extent of the health problems caused by SO_x emissions in these cities. (See Kagawa *et al.*, 1995 for details.)
5. For example, 967 900 t of coal was used to generate 1043.03 million kWh of electricity in Chengdu in 1990. The energy conversion efficiency is calculated to be 23.16% compared to the corresponding 1991 figure for Japan of 39%. The amounts (in kg) of SO_x emissions and air-borne pollutants, respectively, that are generated per kWh of electricity are estimated to be 0.01438 (Chengdu) and 0.00176 (Japan) for SO_x and 0.01774 (Chengdu) and 0.00032 (Japan) for air-borne pollutants (Yoshioka and Ikeda, 1995).
6. See Cambridge Econometrics and Hayami (2000) and China State Statistical Bureau, *Statistical Yearbook of China* (various years).
7. The estimated aggregate energy elasticity (0.6) is based on the totality of these sectorial estimates with a large variance.
8. BC Hydro, a provincial government electric generating corporation in British Columbia, Canada announced recently its plans to purchase CO_2 emission credits for 5.5 million tonnes of greenhouse gases per year from international sources. Such credits will be used in part to offset its expected forthcoming increases in emissions of greenhouse gases: 11 million tonnes from two natural gas-fired

electric power generators being built on Vancouver Island. BC Hydro says it could not find any domestic credit sellers. Among the options it is considering are to outfit a Mexican factory with filters to reduce its emissions and to buy polluting factories and shut them down permanently. Alberta-based Transalta, Canada's largest non-regulated utility, has already reduced its emissions by 1.77 million tonnes (CO_2 equivalent) through several programs of credit purchasing, one of which involved financing an improved digestive process for cattle in Uganda (the aim is to get the cattle to emit less methane). (See *Vancouver Sun*, January 11, 2002.)

9. Also it is illegal for foreigners to conduct surveys in China.
10. For example, we found that the level of air-borne particles is very high, by international comparison, in Chengdu particularly in winter months and that about 40% of the particles come from coal burning. Another 40% of the particles are mineral particles coming from soil as well as construction materials. About 50% of these air-borne particles are micro particles that adversely affect human health, and significant amounts of harmful contaminants such as Pb, Cd, As, Se, B (a), P and acids were detected. The industrial districts of the city were most seriously polluted with such particles. We also found that, because of the geographical formation (basin) of the city, the air-borne pollutants generated tend to stay around the city, making the pollution level remain high. (See Fujimura and Sekine, 1995 for further details.) We also conducted extensive standardized health surveys based on ATS-DLD78 (Ferris, 1978) and the Japanese Environmental Agency (1981). Adults in selected households where the survey was administered were asked to complete survey questionnaires for both themselves and the children who were living in the households between December 1991 and January 1992. All of the questionnaires that were turned in were reviewed by personnel from the Chengdu Environmental Protection Research Institute and the households that returned questionnaires with incomplete answers were asked to complete them. Usable questionnaires were obtained for 2729 children in 3 elementary schools (1403 male, 1326 female; 97.3% response rate) for suburbs, for 2382 children in 4 elementary schools (1184 male, 1198 female; 98.6% response rate) for the city proper, and for 2415 children in 3 elementary schools (1177 male, 1238 female; 93.8% response rate) in industrial districts. To control for residency, only those who had lived at the same addresses for at least 3 years were subsequently chosen for analysis. This reduced the number of usable questionnaires for children to 2980 males and 3026 females. Similarly the numbers of adults who had lived in the same addresses and provided usable questionnaires were 5314 males and 4532 females. Careful statistical analysis of the data controlling for various factors and international comparisons between this survey and a similar survey done in Japan revealed significantly high incidences of lung and throat related health problems associated with the residents in Chengdu. It was also identified that the areas in the city proper and industrial districts in which iron and steel factories were located were found to have particularly high incidences of pollution-caused diseases. (See Kagawa *et al.*, 1995 for further details.)
11. Based on Japanese experience in cost estimation, the following functional forms were assumed for estimating production cost for our Chinese plants. (1) The design and construction cost of a machine with the output capacity of q t/h: $C_d = aq^b$, where a and b are unknown parameters to be estimated ($a = 0.26$ and $b = 0.71$); and (2) (variable) cost of producing n machines with a capacity of q **t** of biobriquette per hour (in translog form): $\ln C_p(q, n) = c + d(\ln q) + (\frac{1}{2})e(\ln q)^2 + \alpha(\ln n)$, where c, d and α are unknown parameters to be estimated ($c = -1.62, d = 0.34, e = 0.25$ and $\alpha = 0.6$). The parameter α represents production scale effects. The market size is given by $M = nq$. The total cost of producing n machines for the market size M is given by $C(q, n) = C_p + C_d$. Our functional form implies two scale effects: one due to the size of output capacity (q) and another due to the number of machines (n) produced for the total marketplace M. Minimizing the average cost ($C(q, 1)/q$) with respect to q provides optimal daily plant output capacity. Table 5 shows optimal output and the number of

machines for various values of market size (Yoshioka *et al.* 2001).

12. Detailed experimental results on the use of sulphur from biobriquette ashes for agricultural soil for corn and wheat crops were obtained by the Shenyang agricultural experimental station and are reported in Nitta *et al.* (2001).
13. Many thousands of these volunteer helpers may not be volunteers in real sense, but the size of the afforestation activity (tree planting) our joint research project team would like to implement is so large in scale that the support of the local government is essential.
14. It is by no means obvious that the underlying economic calculations would lead to abandoning coal entirely as its energy source in Chengdu. Given the world price differential between natural gas and coal which will persist over time, the policy to rely heavily on natural gas will probably not likely be sustainable in the long run. In fact a number of developed countries still rely heavily on coal for various industries including electric power generation even though they produce both coal and natural gas locally.

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